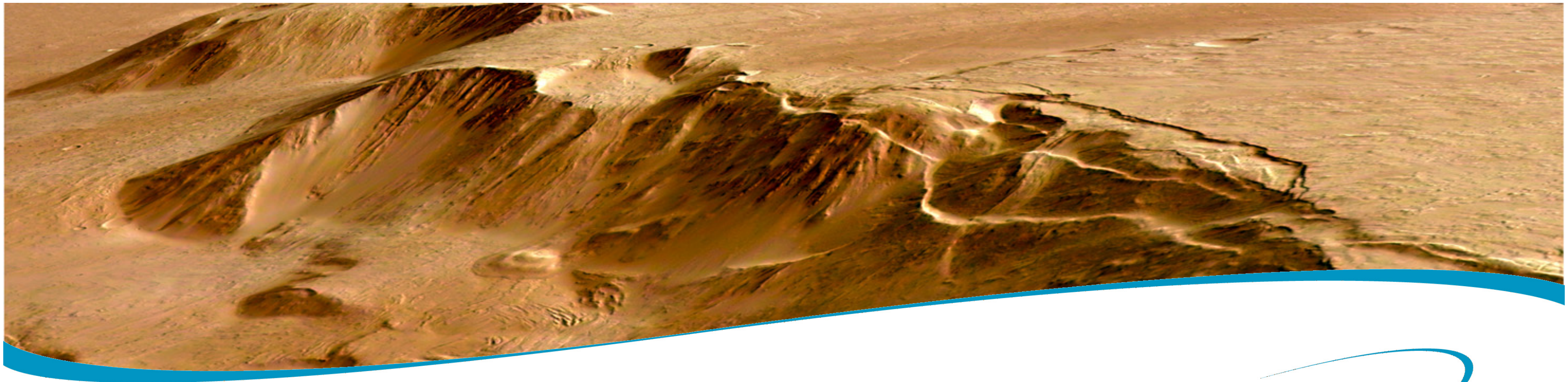

EXOMARS-2016
GNC Approach for Entry Descent and Landing Demonstrator

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Template reference : 100181708K-EN

TAS-I BS-OOS

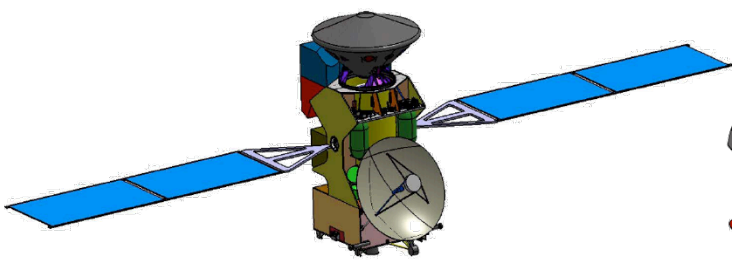
ESA led ExoMars 2016

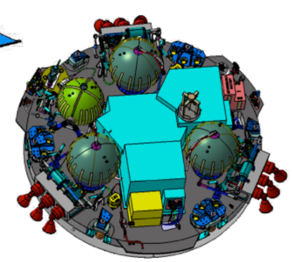
2016 Mission Objectives

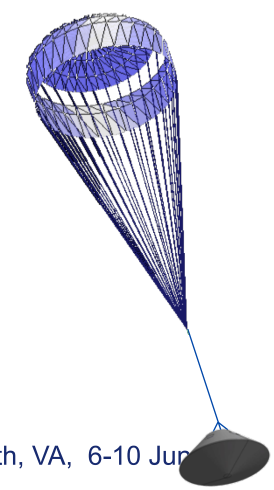
- Provide Europe with the required technologies for successful entry descent and landing of a payload on the surface of Mars
- Perform investigation on the Martian atmospheric trace gases and their sources
- Ensure communications capability for the other future international assets on the surface of Mars

2016 Mission Components

- ESA provided S/C Composite
  - Entry Descent & Landing Demonstrator Module (EDM)
  - Trace Gases Orbiter (TGO)
- NASA provided Launch vehicle

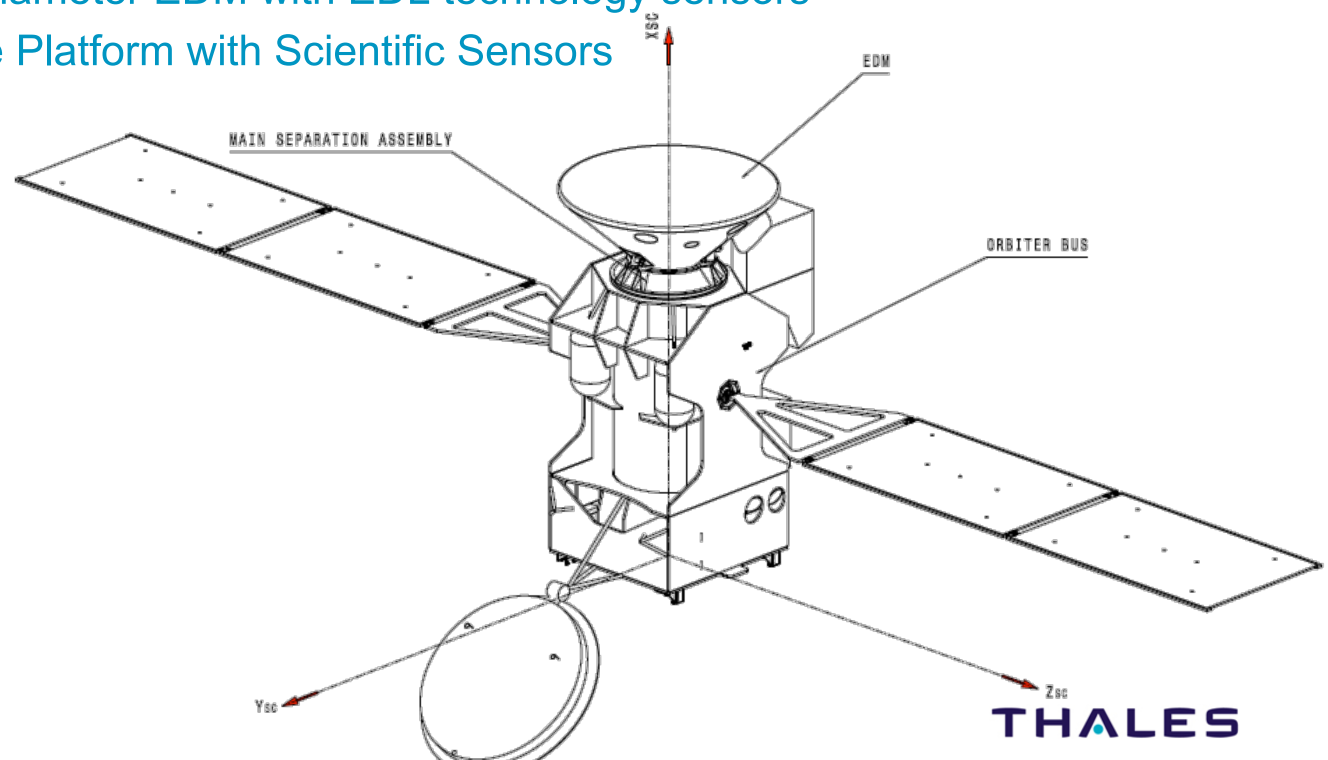






2016 Spacecraft Composite – 4400 kg launch mass

- **Orbiter Module – Trace Gases Orbiter (TGO) – 1365 kg**
  - Orbiter Bus and Orbital Scientific Payload Package of 125 kg
- **Main Separation Assembly (MSA)**
- **Entry Descent & Landing Demonstrator Module (EDM)**
  - 600 kg, 2.4m diameter EDM with EDL technology sensors
  - 280 kg Surface Platform with Scientific Sensors



EDL key facts

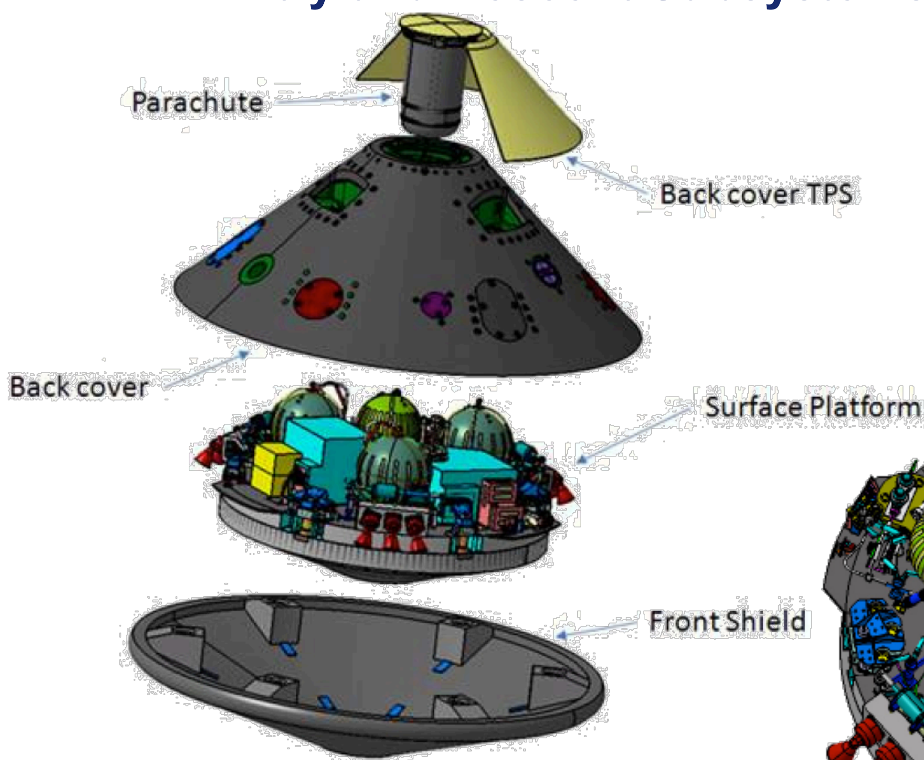
- **Arrival at a fixed date (16-Oct-2016) during Dust Storm Season**
- **Direct entry from hyperbolic approach, prograde entry in daylight**
  - Hyperbolic excess velocity 3.256 to 3.463 km/s
- **Separation from OM oriented at EIP attitude with a Main Separation Mechanism providing both axial relative separation rate of 0.3 m/s and stabilization spin rate of 2.5 RPM at the same time**
- **Entry 3 days after separation – hybernation mode (19-Oct-2016)**
  - Entry velocities: co-rotating 5.70÷5.83 km/s, airspeed 5.97 ÷ 6.03 km/s
- **Deployment of a single parachute (Disk-Gap-Band Huyghens type)**
  - supersonic deployment and deceleration to subsonic terminal velocities
- **EDM sub-modules release strategy with a separation operated at Back Shell/ Front Shield and at Backshell under parachute/Surface Platform**
- **RCS: 3 clusters of 3 PWM engines each, directly mounted on the landed Surface Platform**
- **Active deceleration strategy with g-turn maneuver**
- **Crushable structures for impact load attenuation**

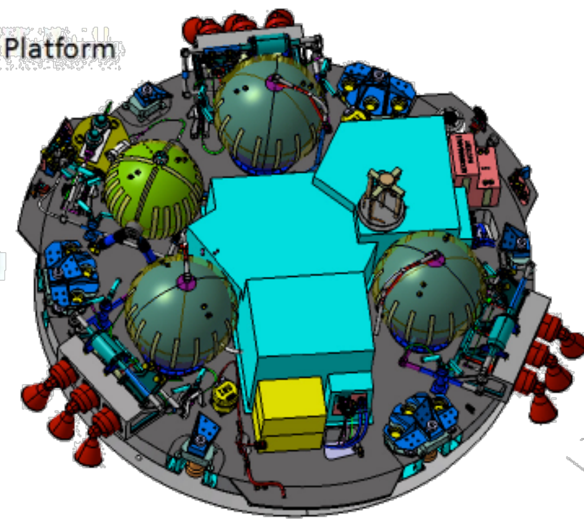
Exomars EDM - Phases

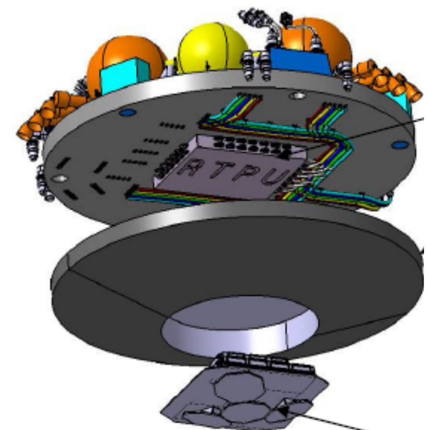
- **ENTRY**
  - Approach (coasting – 3 days from Separation & Hypersonic Braking
- **DESCENT**
  - Parachute Deployment, Front Shield separation, Radar activation, Surface Platform separation
- **LANDING**
  - Engines firing, GNC for Active Control (g-turn with parachute avoidance manoeuvres), Engines shutdown, Free-fall and touch down / impact on crushable structure

Image Courtesy of ESA

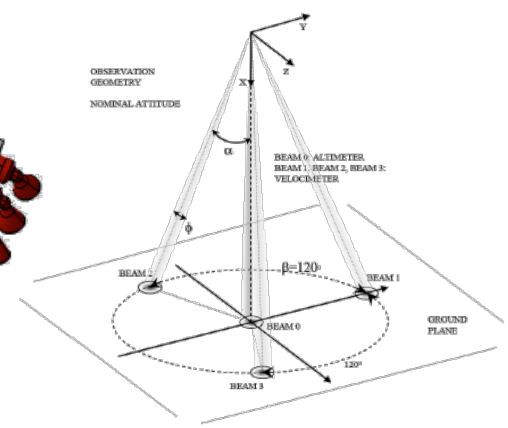
EDM: Entry and Descent Subsystems + Surface Platform



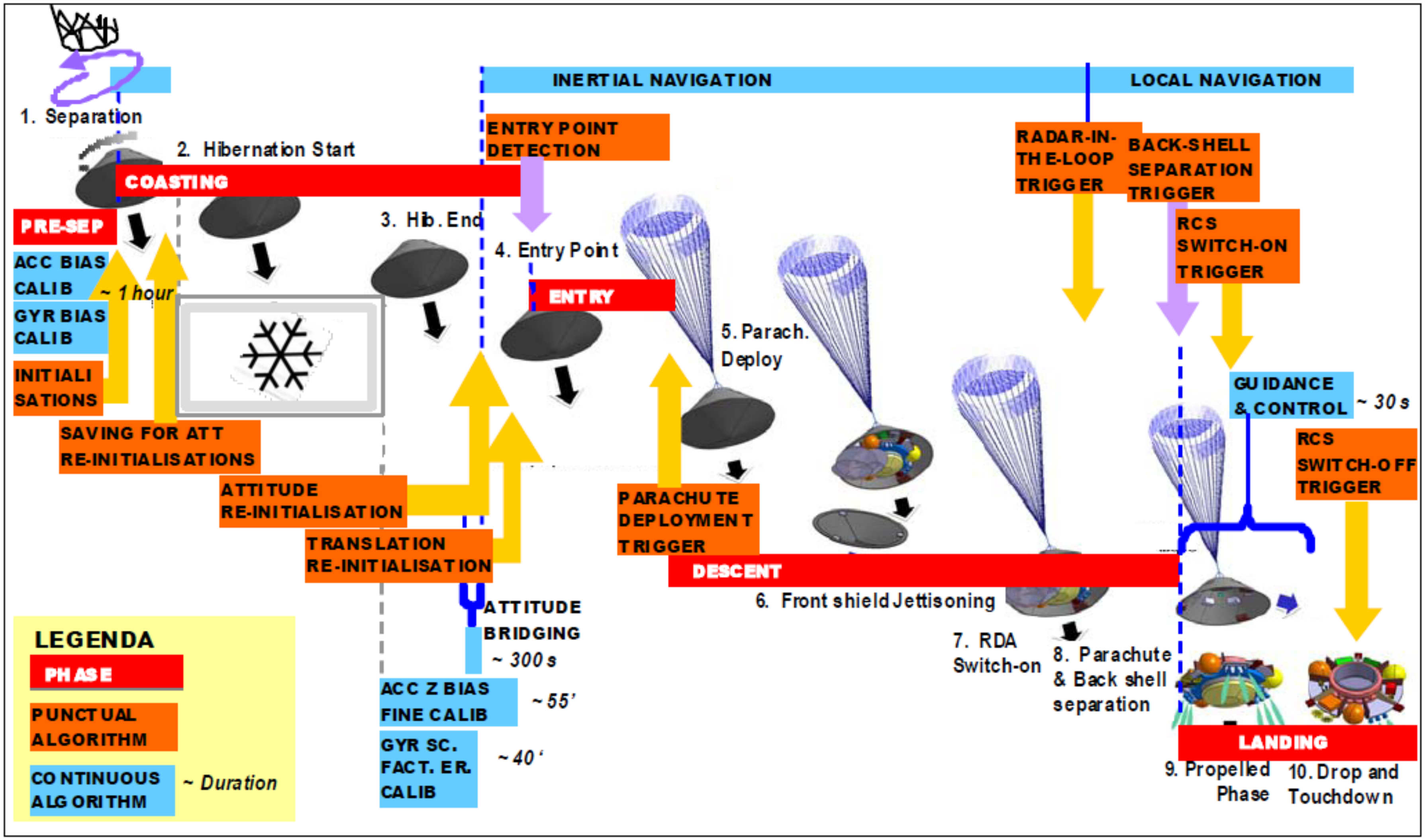




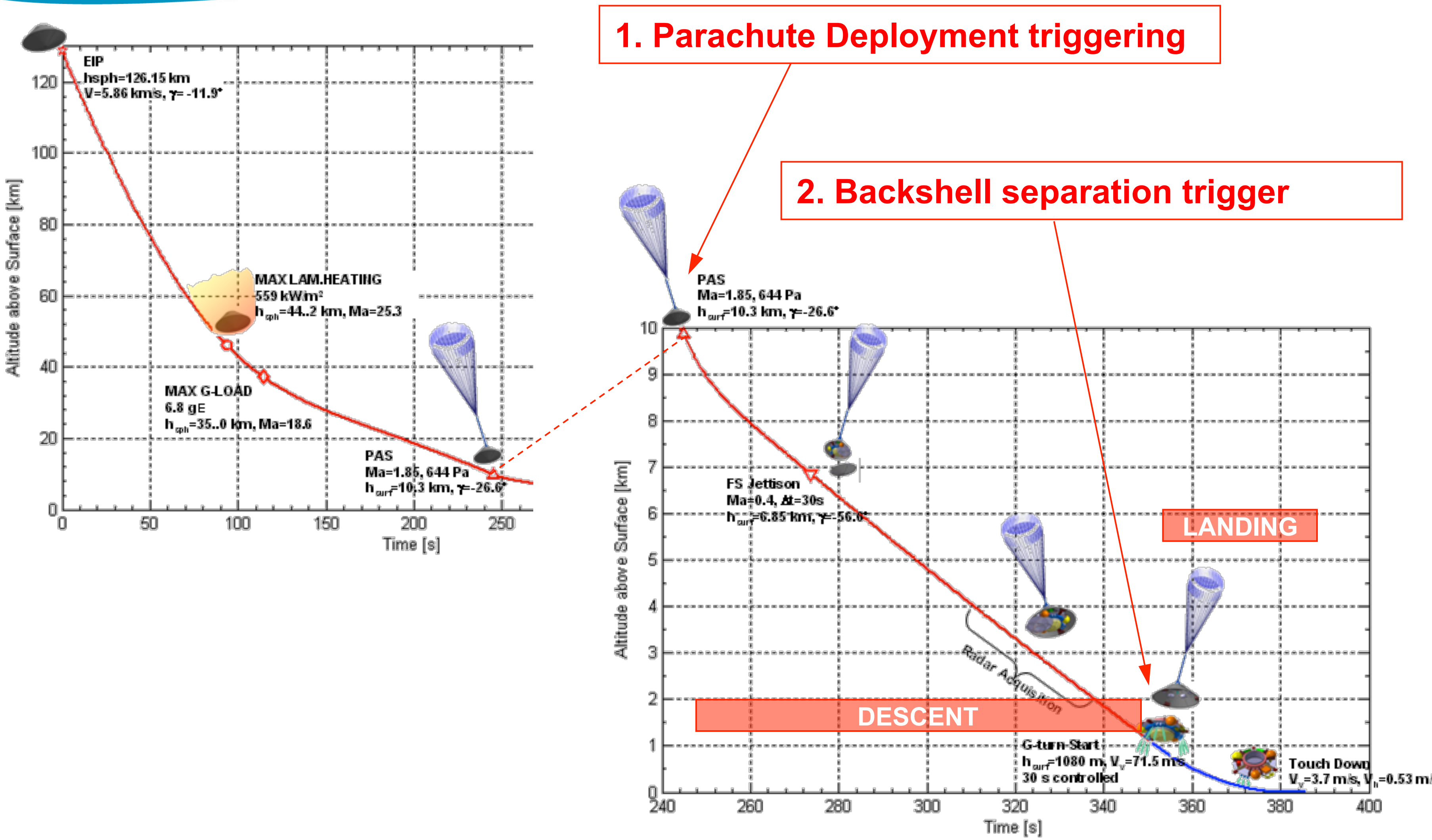
RDA Assembly



EDM Mission Phases and GNC Tasks



Key GNC Tasks for successful EDL



TAS-I BUOOS

EDM Mission Phases and GNC Tasks

Key tasks for successful EDL

- **Parachute Deployment Triggering**
  - ➢ Must be performed in the valid Mach - dynamic pressure window
    - Early deployment → High dynamic pressure and inflation loads, canopy stability and drag oscillations
    - Late deployment → No altitude margin for Descent and Landing sequence
  - ➢ Key events as Front Shield jettisoning, RDA RF channel switch on based on timer from Parachute Deployment trigger
    - Need sufficient time for RDA measurement convergence (non-ambiguous signals)
    - Radar in the loop trigger and Relative terrain navigation (navigation solution hybridization)
- **Backshell separation trigger**
  - ➢ Initiation of the landing phase – propelled phase
  - ➢ Crucial for velocities cancellation within a given propellant budget
    - Under relevant variations of atmospheric conditions (density, winds)
- **RCS cut-off and final drop**
  - ➢ Crucial wrt slopes and rocks, 2m drop altitude nominal

ThalesAlenia Space
A Thales / Finmeccanica Company

Descent Phase – Deployment triggering

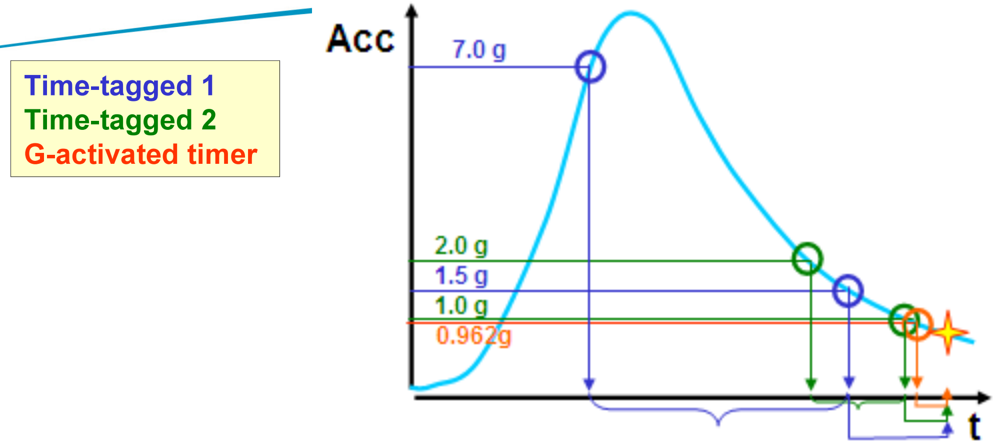
G-activated timer

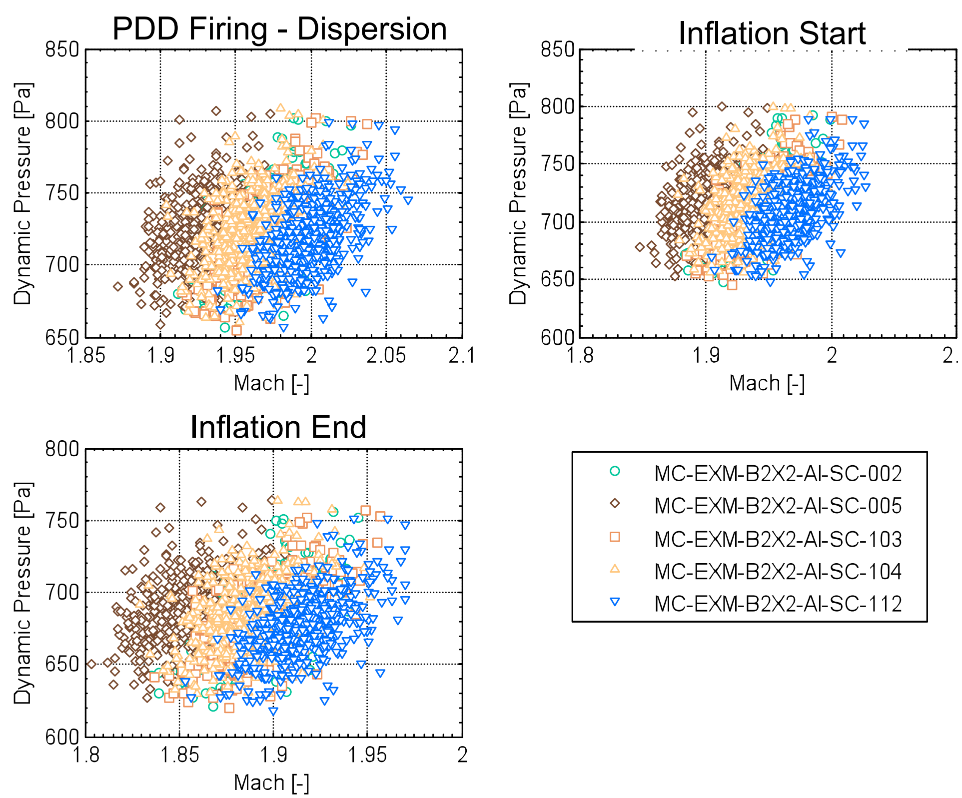
Several algorithms tested

- **Optimal performances wrt to given parameters**
  - Altitude, Mach, dynamic pressure
  - Optimal → EDL parameter updating → tuning to expected atm. variability

Need for robustness

- **A simple G-activated timer proved maximum robustness wrt environmental uncertaintie**
  - Deployment window met wit no need of pre-EDL in-situ observations
- **7.8-11.3 km AGL (10.3 km nominal): 2.5 km uncertainty**





Landing - Propelled Phase GNC

Landing phase

- **Starts when a combination of predicted altitude and vertical velocity deemed suitable for terminal braking within the available propellant budget**
  - 55÷78 m/s vertical velocity (atmospheric variability), 0÷30 m/s horizontal velocity (worst case mesoscale)
- ***Separation trigger,***
  - 1 second free drop → clearance between BCV and ESP
- ***Closed loop trigger***
  - RCS becomes active with the Guidance and Control functions
  - 3 seconds thrusters warm-up, used for de-spin and velocity maintenance (coarse mode)
- ***Backshell Avoidance Manoeuvre (BAM) trigger***
  - Backshell avoidance, g-turn and ESP braking is initiated. Prescribed manoeuvre time with fixed nominal T2W within RCS duty cycle of 50%
- **Pre-Switch-Off Trigger**
  - No RDA measurement below 10 m → transition from RDA-based navigation to IMU-based
  - 1.5÷2 s before the manoeuvre termination the navigation laws freeze angular and vertical acceleration reference profiles to avoid destabilizing effects (singularitues for 0-attitude 0-Vh)
- ***Switch-off trigger***
  - RCS shut down and the ESP free fall.
  - Nominal altitude of 2 m and a Nominal vertical velocity of 0 m/s

GNC – Descent and Rotation Control

Descent Control Loop

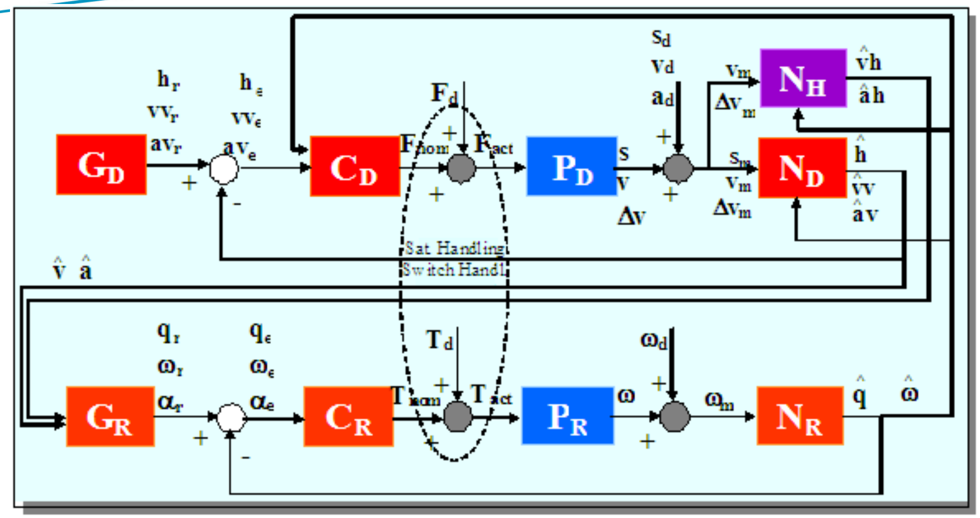
- narrower bandwidth, control of descent profile (altitude and vertical velocity)

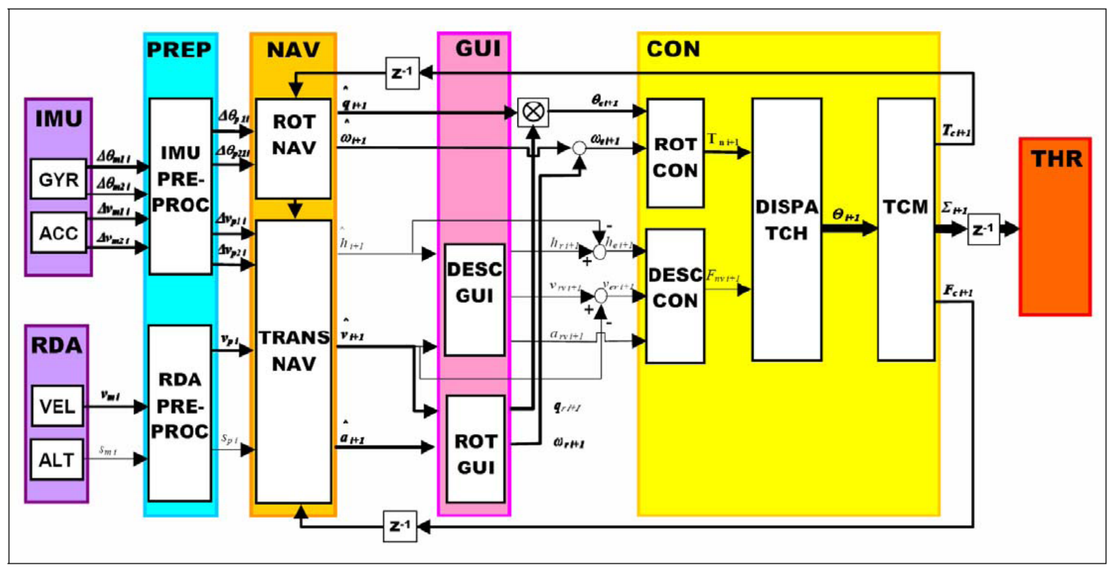
Rotation Control Loop

- wider bandwidth, control of attitude and angular rate

Strong Coupling

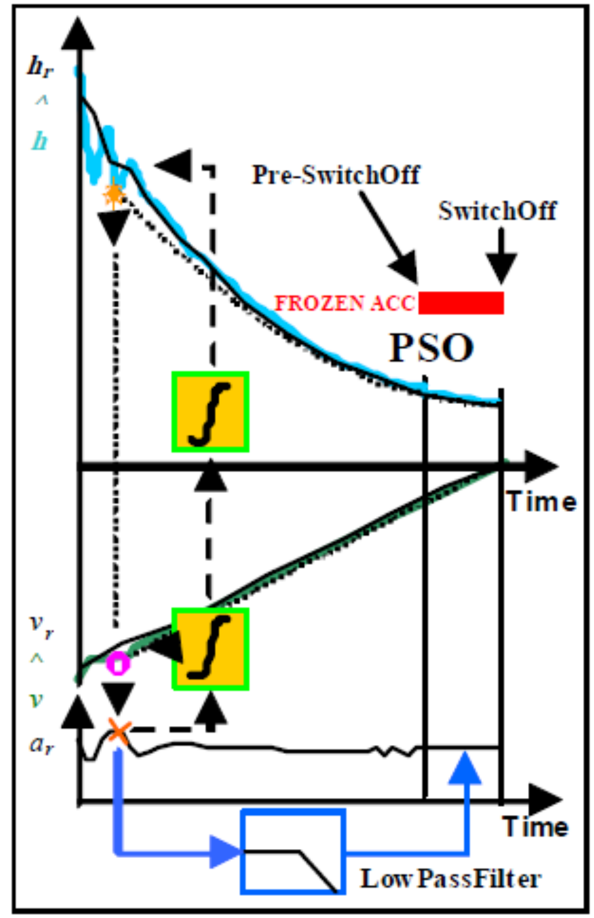
- Vertical deceleration driven by attitude control
- Attitude quaternion also used to convert the RDA from sensor frame Local Vertical frame
- Control force and torque transformed in dispatched command to the 9 thrusters





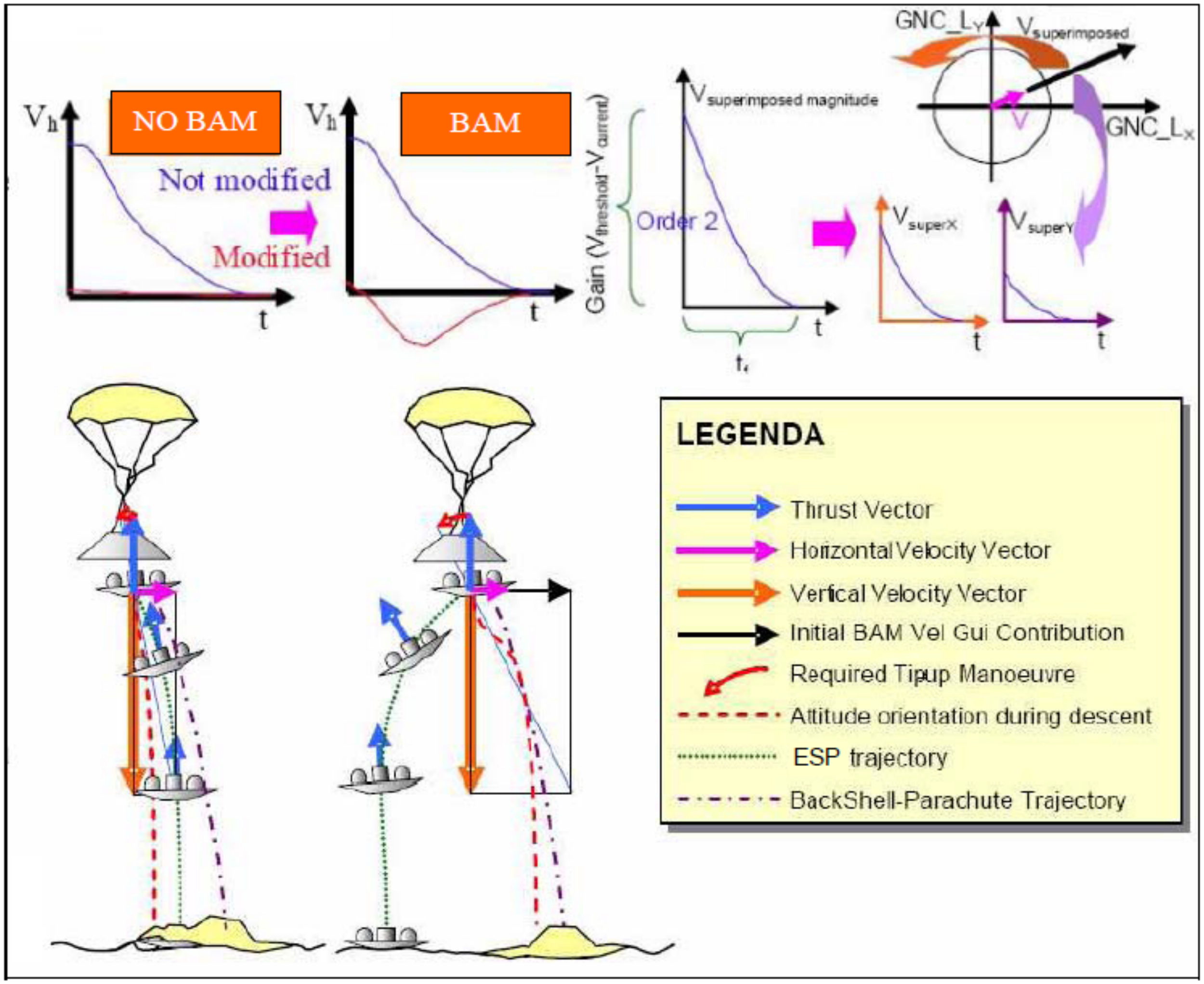
Closed Loop Trigger

- **Aim**
  - Concurrent cancellation of vertical and horizontal velocities as well as angular rates and attitude leveling
- **Targeting of constant deceleration profile**
  - Reference deceleration planned using the estimated altitude and vertical velocity
  - Reference deceleration re-planned at each instant
  - Updating terminated at the *pre-switch-off* to avoid instabilities and numerical singularities.
  - 22-30 s manoeuvre time depending on initial mass (260-300 kg)
- **Pre-Switch-Off**
  - In the last portion of the manoeuvre the reference acceleration is a frozen filtered value (reference decelerations accrued in previous instant of the propelled phase). No valid RDA below 10-12 m



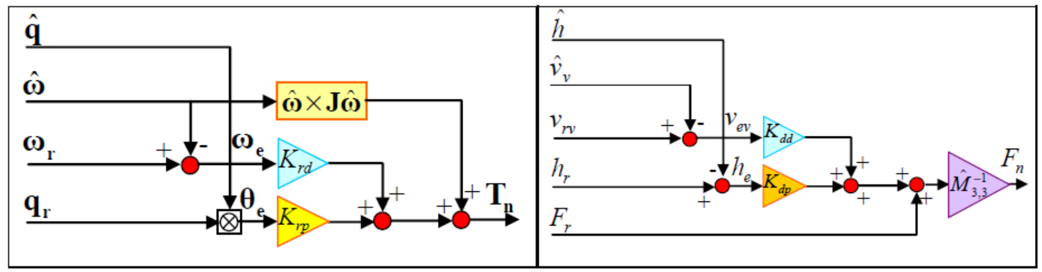
BAM - guidance

- determines the amount of intervention to be applied – large for low hor.velocities
- augments the horizontal velocity components in input to the reference quaternion computation through fictitious superimposed terms
- reduces progressively the application of the superimposed terms and nullifies these terms after a prescribed time



Rotation and descent control structure

- **Feedback term**
  - computed from reference and estimated states (PD law)



- **Feedforward term**
  - based on the reference control action predicted for the next thruster activation
- **Compensation term: introduced to cancel the known part of the non linearities and of the environmental disturbances**
  - Model-based portion, cancels most of the known perturbations affecting the performances

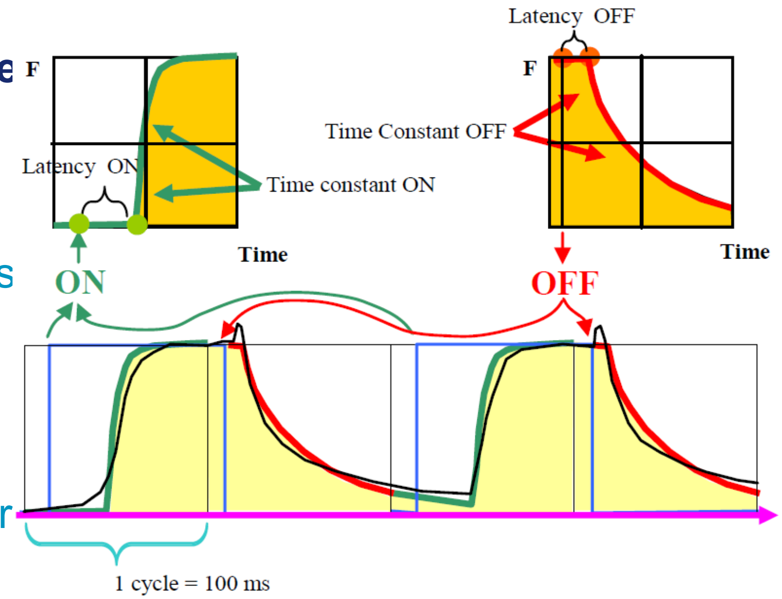
Requested force and torque computed by the rotation and descent control blocks must be verified against *command saturation*

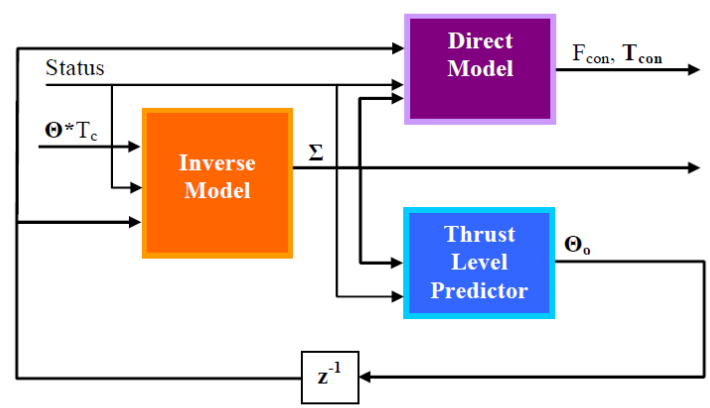
- **Resources must be allocated taking into account that**
  - Descent control, requires almost the same thrust level during the whole controlled phase (50% duty cycle allocated)
  - Attitude control requires a strong unbalance of the thrust level in the various thrusters for the first 4-5 seconds after BAM trigger
- **Command dispatching to 9 thrusters with pseudo inverse and dedicated pulse width modulation strategy**

Command dispatching, PWM, CHT40 thruster model

Thruster Command Module

- **CHT400 thrusters proven in space for satellite control**
- **Dedicated operation mode for 10 Hz control cycles**
  - time constants of the rise and decay profiles and the latencies of the ON and OFF commands to be accounted for in the PWM scheme
  - Split into a ***inverse model*** and a ***direct model***, selected upon thruster status trigger → model based impulse allocation
- **Thruster dynamic characterization tests performed**
  - Characterization of cold start profiles
  - Characterization of the performance parameters for several inlet pressures
  - Derivation reference performance (for GNC inverse model) and real performance (perturbed, for E2E simulations)
- **Operation at 10 Hz achieved**





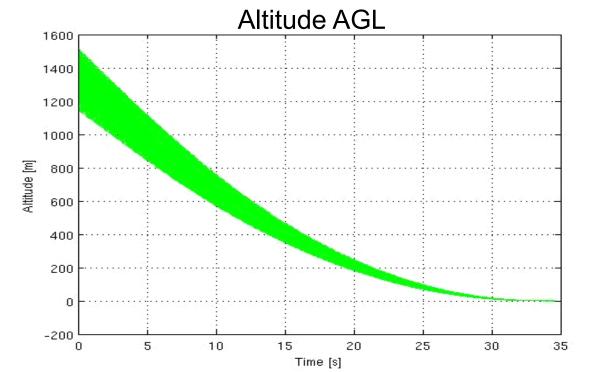
Verification of the stability for Descent GNC

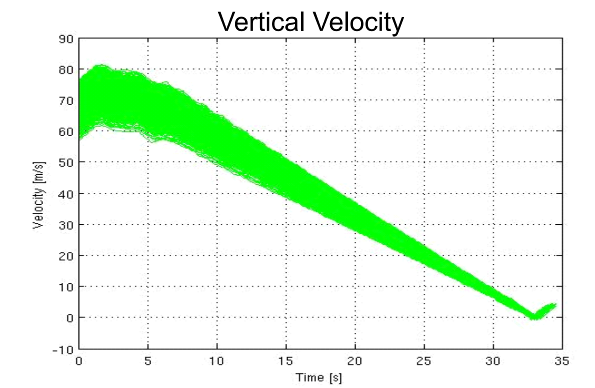
- **Analytical methods based on Embedded Model Control**
  - Allows verification od stability and performance of the implemented GNC
  - Verification of robustness through assessment of the embedded model (in the control structure) with respect to design model including uncertainties
- **MonteCarlo Simulation**
  - Dedicated campaign to verify the performance prediction with HiFi models
  - GNC design simulator models migrated to functional E2E simulator
    - developed in TAS-I, full 6-dof simulation of EDL
  - Progressively increasing complexity and fidelity for E2E simulator
    - Inclusion of functional modes for bus data communication to be implemented

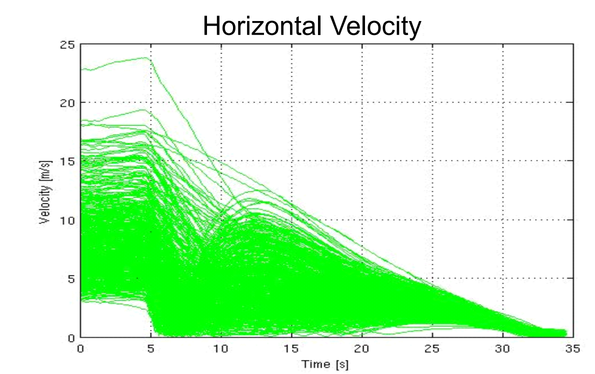
Estimated performance conservative wrt MC

No	Performance variable	Unit	Target (max)	Analytic (max)	Monte Carlo $1-\alpha=0.997$
0	Angular rate (half cone)	rad/s	0.15	0.135	0.058
1	Attitude (half cone)	rad	0.125	0.094	0.11
2	Vertical velocity	m/s	0.8	0.29	0.64
3	Altitude	m	1.0	0.88	0.81
4	Horizontal Velocity	m/s	1.6	0.98	0.87

Performance – Descent and Impact







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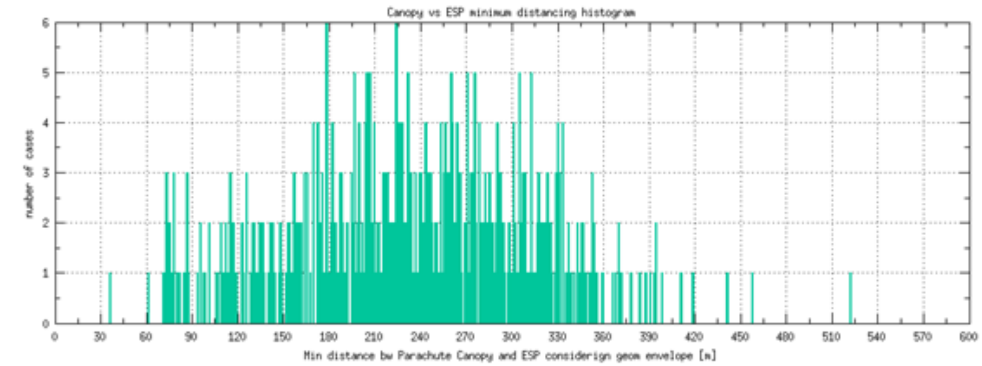
Parameter	units	Median	1:99%ile (90%CL)
FS Jettisoning			
Altitude AGL	[km]	6455	**4093 : 7747**
Vertical Velocity (Co-rotating)	[m/s]	83	76 : **87**
Radar RF-On			
Altitude AGL	[km]	5640	**3285 6940**
Radar in the Loop Trigger			
Altitude AGL	[km]	1925	**1900 : 1944**
Vertical Velocity (Co-rotating)	[m/s]	69.4	56.8 : 78.8
Orizontal Velocity (Co-rotating)	[m/s]	9.7	1.4 : **30.6**
ESP Separation Event			
Altitude AGL	[m]	**1360**	**1130 : 1562**
Vertical Velocity (Co-rotating)	[m/s]	67.7	**55.7 : 78.3**
Orizontal Velocity (Co-rotating)	[m/s]	9.7	0.3 : **29.2**
Off-Vertical Angle	[deg]	2.1	0.1 : 9.6
Closed Loop Triggering			
Altitude AGL	[m]	**1283**	**1067 : 1473**
Vertical Velocity (Co-rotating)	[m/s]	71.6	**59.6 : 82.2**
Orizontal Velocity (Co-rotating)	[m/s]	9.7	0.3 : 29.2
Off-Vertical Angle	[deg]	5.0	0.2 : 18.5
ESP Drop Event (RCS swith-off)			
Altitude AGL	[m]	2.0	**1.4 : 2.7**
Vertical Velocity (Co-rotating)	[m/s]	0.1	**-0.5 : 0.6**
Horizontal Velocity (Co-rotating)	[m/s]	0.2	0.0 : 0.7
Off-Vertical Angle	[deg]	2.7	0.3 : 5.9
ESP Touch Down Event			
Vertical Velocity (Co-rotating)	[m/s]	3.7	**2.8 : 4.4**
Horizontal Velocity (Co-rotating)	[m/s]	0.2	0.0 : **0.7**
Propellant Consumtption			
Propellant Consumption Tank 1	[kg]	9.4	8.6 : 10.0
Propellant Consumption Tank 2	[kg]	9.2	8.5 : 9.8
Propellant Consumption Tank 3	[kg]	10.1	9.3 : **10.9**
Total Propellant Consumption	[kg]	28.7	26.5 : **30.5**

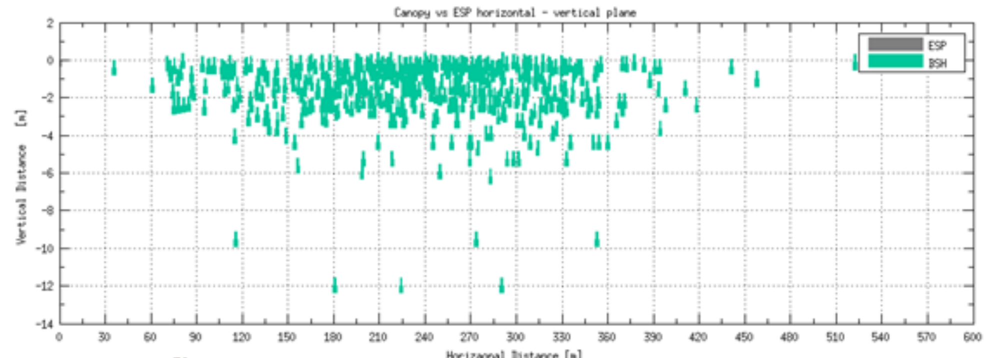
BAM - Performance

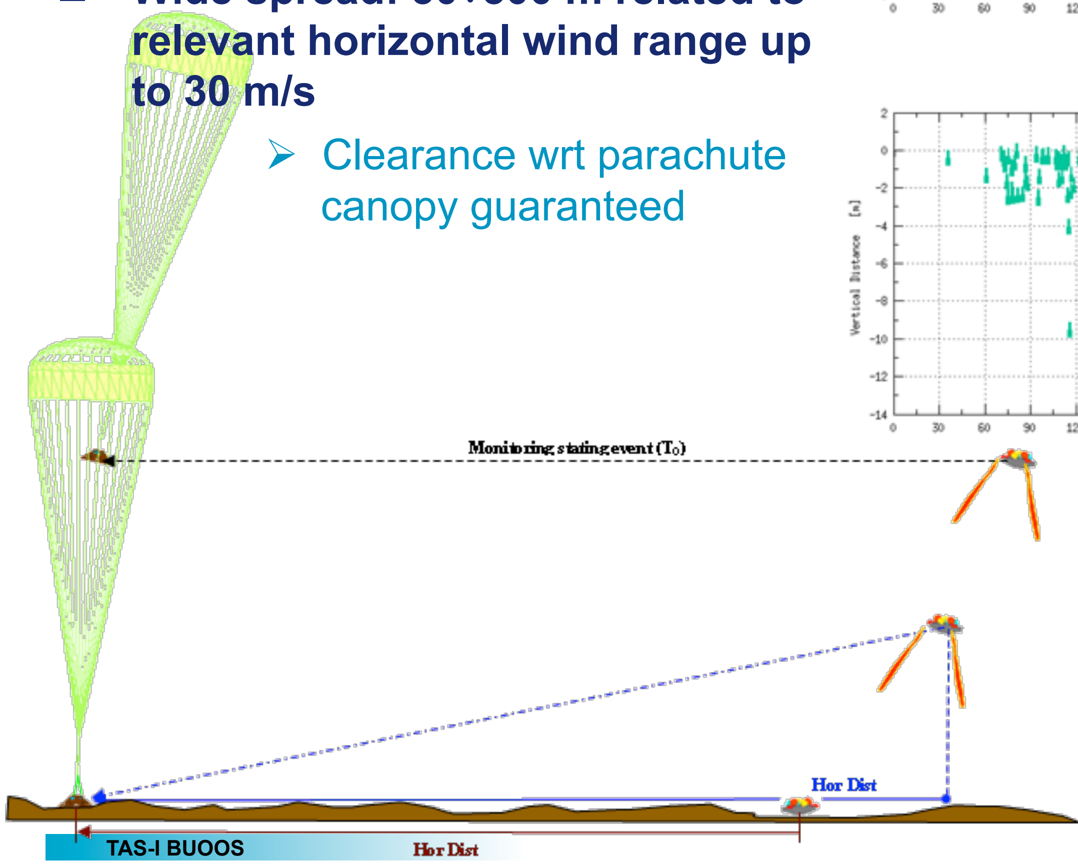
BAM effectiveness: BCV always "overtakes"

Minimum distance to be guaranteed

- **Wide spread: 30÷500 m related to relevant horizontal wind range up to 30 m/s**
  - Clearance wrt parachute canopy guaranteed







Simulation Set: MY24

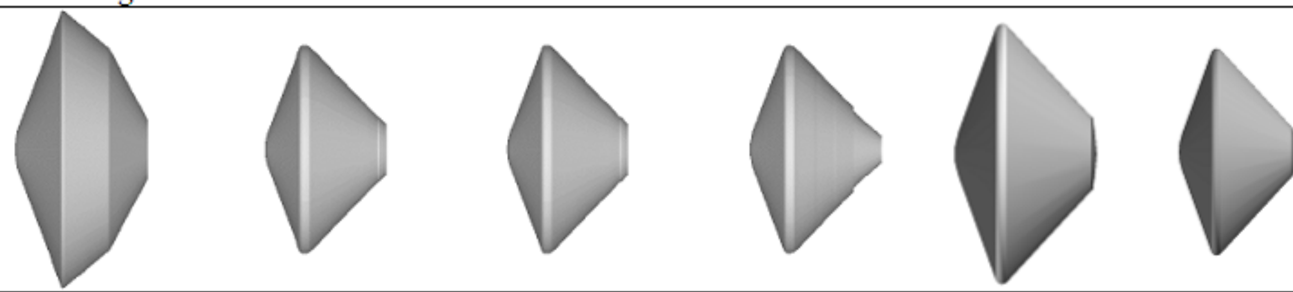
Conclusions

- General overview of GNC for the ExoMars 2016 European provided
- Key focus on the landing phase, the core of the mission implying a loop of control closed on PWM retro-rockets
  - Algorithmic functional architecture and verification strategies (analytic assessment and Montecarlo simulations)
- Performance targets compatible with crushable structure limits appear to be reachable.
  - Margins adequate to account for the uncertain factors and the model factors
  - Requirements at touch down verified
- Future work
  - Model improvement from unit and subsystem tests
    - Engines response at several feed pressures (performed)
    - RCS hydraulic mockups
    - Radar Doppler Altimeter field tests
    - Parachute High Altitude Drop Tests
  - Simulator upgrade from performance model and inclusion of functional layers for GNC modules

BACKUP SLIDES

Comparison of Exomars EDM to previous missions

- **Starting point – Use of databases in open literature**
- **Work plan – improve and refine for the specific Exomars mission**
  - specific EXM entry velocity and ballistic factor, specific season, flight profile not fully covered by the previous missions
- **Dedicates numerical and experimental programme for AEDB and ATDB building**

	Viking	Pathfinder	MER	Phoenix	EXM-DM	EXM-EDM
						
Diameter, m	3.5	2.65	2.65	2.65	3.4	2.4
Entry Mass (kg)	930	585	840	602	1200	600
Relative Entry Velocity (km/s)	4.5	7.6	5.5	5.5	5.07	5.98
Relative Entry FPA (deg)	-17.6	-13.8	-11.5	-13.2	-12.2÷-10.2	-12.4÷-11.7
m/(CDA) (kg/m2)	64	62	90	65		80
Xcg/D	-0.22	-0.25	-0.25	-0.25	-0.255	-0.26
Ma at Parachute Deployment	1.1	1.6	1.85	1.65	1.95	1.95
Hypersonic α_{trim} (deg)	-11	0	0	0	3	3
Control	RCS Damp.	Spinning	Spinning	Non-Spinning	Spinning	Spinning
Entry type	Orbit	Direct	Direct	Direct	Orbit Retrog.	Direct Posig.

Exomars EDM vs MER

Data	Exomars EDM 2016	MER-B Opportunity
Entry date	**19/10/2016**	**25/01/2004**
Season	Late Summer	Winter
Landing site	Meridiani	Meridiani
Landing time (GST)	19-Oct-16 03:48 PM	25-Jan-04 04.55 AM
EIP Time (GST) (Entry beginning)	19-Oct-16 03:48 PM	25-Jan-04 04.45 AM
Mars Solar Longitude (LS)	244.7	338.99
Local True Solar Time (LTST) at entry	13:03	12:08:00
Local True Solar Time (LTST) at landing	14:22 - 14:35	13:23:00
Latitude at EIP	4.13N - 5.54N	4.1S
Longitude at EIP	17.3W - 16.6W	18.95W
Latitude at Landing	1.9S	-2.06N
Longitude at Landing	6.1W	354.01E
Landing Altitude /MOLA [km]	-1.44	-1.44
Entry type	posigrade	posigrade
Entry point [km]	121.5	125.92
Entry velocity (inertial) [m/s]	5912 - 6029	5720
Entry velocity (relative) (Co-Rotating) [m/s]	5663 - 5779	5480
Entry FPA (inertial) [deg]	Corridor	-11.47
Entry heading [deg]	118 - 125	83
Diameter [m]	2.4	2.65
Nose Radius [m]	0.6	0.66
Entry Mass [kg]	600	832.2
Ref Ballistic Factor [kg/m2]	77.86	88.88
Parachute diameter [m]	12	15.09
Parachute drag	0.4	0.4
Nominal parachute opening Mach	1.95	1.86
Nominal Parachute opening Dyn.P [Pa]	783	747
Nominal Parachute opening Altitude [km]	10.1	8.7
Nominal Parachute opening FPA	-22.8	-26.54
Heat Shield jettison time/parachute	40 s	20 s
HS jettison Mach	0.4	0.49
Peak Laminar heating (kW/m^2)	602	422
Total heat load (MJ/m^2)	36.87	27.1
Peak Deceleration	9.13g	6.4g